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Reinforcement of the Seismic Interaction of Soil-Damaged Piles-Bridge by Using Micropiles

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ABSTRACT

This paper presents a three-dimensional numerical model of soil-damaged piles-bridge interaction under seismic loading. This study focuses on the effect of developing plastic hinges in piles' foundation on the seismic behavior of the system. Several field investigations on seismic damages due to recent strong earthquakes have confirmed the decisive role of the plastic hinges in the piles in the seismic behavior of the system. In particular, this study is interested in evaluating the proposed approach for strengthening the system of soil-damaged piles-bridge. The proposed approach is based on using micropiles significantly promoting the flexibility and ductility of the system. This study was carried out using a three-dimensional finite differences' modeling program (FLAC 3D). The results confirmed the considerable effect of developing concrete plasticity in the piles' foundation, which reflects in changing the distribution of internal forces between the piles. Results show the efficiency of using micropiles as a reinforcement system. The detailed analysis of the micropiles' parameters shows a slight effect of pile-micropile spacing. The use of inclined micropiles leads to attenuation of internal forces induced in the piles and the micropiles themselves.

KEYWORDS: Interaction, Piles, Concrete, Seismic design, Plasticity, Three-dimensional modeling, Micropiles.

INTRODUCTION

Often, piles ensure the stability of structures located in seismic zones, but under strong seismic loadings, they are subject to efforts exceeding the allowable limit of seismic resistance. These efforts are particularly dangerous when the piles are installed in nonlinear soil. Post-seismic observations and analysis showed the fundamental role of soil-foundation-superstructure in determining the seismic damage suffered by piles and structures (Kagawa, 1980; Mizuno, 1987; Boulanger et al., 1998-1999; Miura, 2002, …). In case of strong seismic loading, nonlinearities of the soil and the structure can play a decisive role. During seismic loading with high intensity, plastic hinges probably develop in the piles. In the literature, there are several models of concrete behaviour, particularly the elastic-perfectly plastic model; other damage models may take into account the reduction in elastic rigidity and development of irreversible deformations. In seismic design, the development of plastic hinges is allowed in specific locations (in heads as example). In fact, these plastic hinges will absorb the oscillation induced by the seismic loading and thereby limit the resultant stresses. In this study, we analyze the influence of these plastic hinges on the seismic response of the system. The plasticity of the concrete piles is governed by a plastic

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moment M_p which is the maximum allowable bending moment of the pile. Cakir and Mohammed (2013) studied the seismic retrofitting of historical masonry bridges using micropiles and the seismic performance of this technique. Likewise, Momenzadeh et al. (2013) confirmed the micropiles' seismic retrofit efficiency in poor soil conditions with high structural load demands of the San Francisco Bay area bridge. Furthermore, Doshi et al. (2017) have analyzed the seismic behavior of soil-piles-micropiles-bridge and confirmed the beneficial effect of the added micropiles in reducing settlement, bending moment and shear force. Ousta and Shahrour (2001) studied the seismic behavior of micropiles in saturated soils. Sadek and Shahrour (2003) showed that the inclination of micropiles results in an improvement of lateral stiffness, bending moment and axial force. Alsaleh and shahrour (2006) confirmed that nonlinearities of the soil and micropile-soil interface have a significant effect on the seismic response of the micropiles' group as well as that of the structure. The research conducted in this study provides a thorough analysis of the soil-pile-bridge under seismic loading. Particular attention is paid to the influence of nonlinearity of concrete piles and the behavior of soil-pile-bridge reinforced by adding a group of micropiles. The study is carried out using a three-dimensional model by means of the calculation code (Flac 3D).

Soil-Pile Structure System and Numerical Model

The model consists of a group of piles implanted in soil. The modeling of the behavior of such system under seismic loading requires specific methods to take into consideration the interaction between those different components; namely, the soil-piles, pile-pile, piles –cap interaction and all piles-cap-soil with the structure. The boundaries of the model should be put sufficiently away from the structure to minimize the effect of wave reflection which leads to a dense mesh. To overcome this difficulty, we use specific borders which prevent the waves from reflecting on the model. FLAC 3D is used in this study. This code uses the Lagrangian representation of movement. It is based on the explicit finite difference method to solve the equations of dynamic equilibrium.

Reference Example (Elastic)

The reference example consist of a group of (2*3) floating piles with length (L_p = 10.5 m). The group is implanted into a layer of homogeneous soil with a depth of (15 m) and embedded in a cap of (1 m) thickness (Figure 1). The characteristics of soil, piles and superstructure are given in Tables (1) and (2). The mechanical and geometrical characteristics of the reference example are plotted in Figure (1.a). The pile heads (D_p=80 cm) are embedded in a cap of thickness (e_c =1m) with rigid contact; spacing between piles is (S =3.75D_p =3 m). To avoid the complexity of soil-cap interaction, the cap was placed (0.5 m) above the soil. In this reference example, the behavior of soil-pile-structure is assumed to be elastic with Rayleigh damping for the soil; the factor of damping used is (5%) for the soil and (2%) for the structure. The fundamental frequency of soil is (0.67 Hz). The superstructure is modeled by a column which supports a lumped mass in its head (M=350 tons). The rigidity of the superstructure and its frequency (assumed fixed at the base) are equal to K_{st} = 86840 kN/m and F_{st} = 2.5 Hz. They were determined by the following expressions:

$$k_{st} = \frac{3(E_{st}.I_{st})}{H^3_{st}}$$

$$F_{st} = 1/2\pi\sqrt{\frac{K_{st}}{m_{st}}}$$

The frequency of the superstructure, taking into consideration the soil-structure interaction, is $f_{st,\,flex}$ = 1.1 Hz (including SSI).

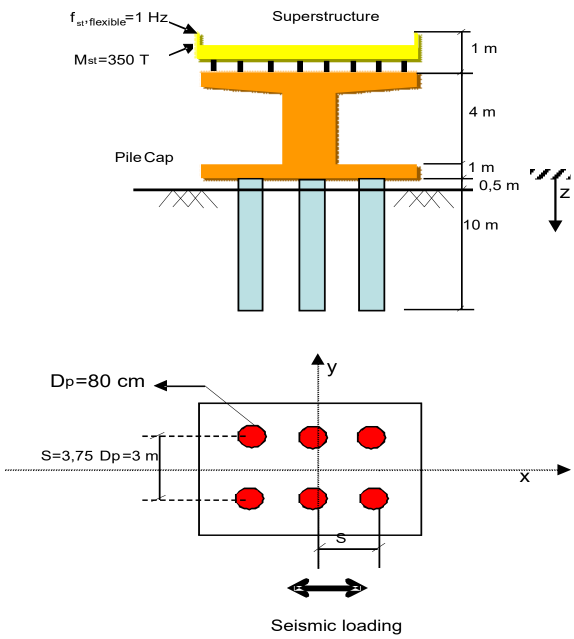
Table 1. The elastic property of the soil and piles' materials

Material	Diameter (m)	Mass Density ρ (kg/m^3)	Young Modulus E (Mpa)	Poisson ratio ν	Damping ratio ξ (%)	Height (m)
Pile	0.80	2500	20000	0.3	2	10
Soil		1700	8	0.45	5	15

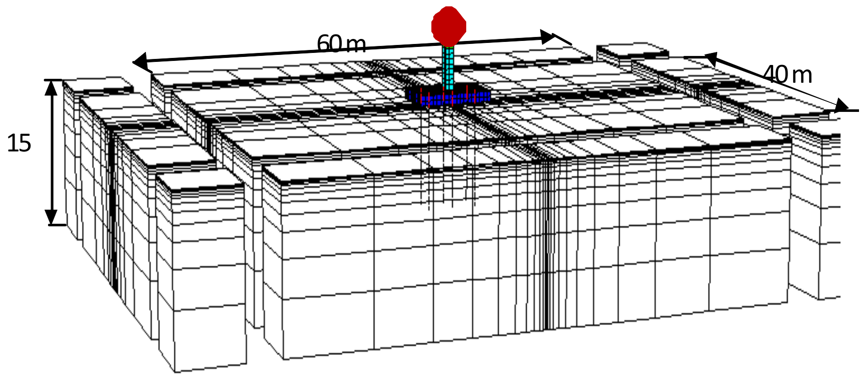
Table 2. The elastic property of the superstructure

ρ_{st} (kg/m3)	E_{st} (Mpa)	ν_{st}	ξ_{st} (%)	Masse (Tonne)
2500	80000	0,3	2	350

ρ, E and ν are the density, Young modulus and coefficient of Poisson. ζ is the factor of damping. D_p is the pile diameter. E*A and E*I are the axial and bending stiffness. The used mesh shown in Figure (1.b) includes (3856) zones of (8) nodes and (138) three-dimensional beams of 2 nodes. The mesh was refined around the piles and near the superstructure where inertial forces induce high stresses.



a) System geometry



b) 3D numerical mesh with absorbing boundaries (138 beam elements and 6978 nodes)
Figure (1): Problem under consideration

Seismic Loading (Real)

The seismic loading chosen in this research is the one recorded in Kocaeli, Turkey on 17/08/1999 (Station AMBARLI; KOERI source). The seismic loading is applied as a speed at the base of the soil as shown in Figure (2). The maximum amplitude of this loading is (40 cm/s) (maximum acceleration =0.247 g).

The spectrum of Fourier corresponds to the used seismic loading illustrated in Figure (2). We note that the frequencies involved are less than (3) Hz with a maximum peak for (F= 0.9 Hz), which is between the fundamental frequency of the soil (F1 = 0.67 Hz) and the frequency of the structure (Fss = 1.1 Hz). Also, note that a first peak is observed for frequency (F = 0.6 Hz), which is very close to the fundamental frequency of the soil.

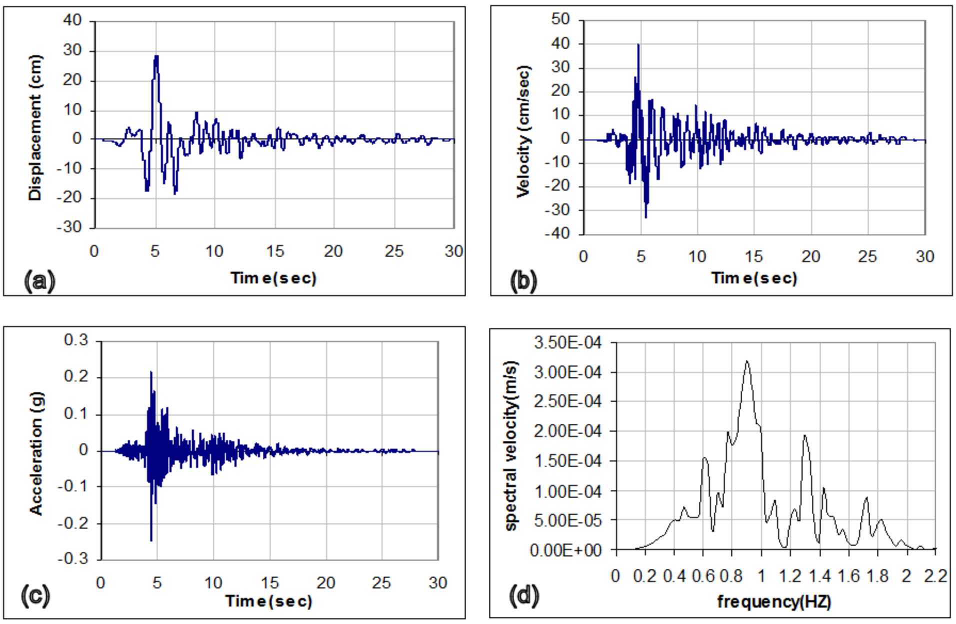


Figure (2): Kocaeli earthquake record (1999)
a) displacement, b) velocity, c) acceleration, d) Fourier spectra of velocity component

Table 3 shows the efforts induced in the piles under Kocaeli earthquake loading. In order to compare the obtained results, the induced efforts are normalized to inertial forces of the superstructure as follows:

Table 3. Reference example: response of a group of (2*3) piles under Turkey loading (1999)

Seismic Loading	α_{st} (m/s²)	α_{Cap} (m/s²)	Internal Forces				Normalized Forces	
			Central Piles		Corner Piles		Corner Piles	
			T_{max} (kN)	M_{max} (kN.m)	T_{max} (kN)	M_{max} (kN.m)	T^*_{max}	M^*_{max}
Turkey	11.28	8.385	675.8	954.4	1016.1	1099	0.196	0.05

$$T* = \frac{T}{T_{cap}}$$

$$M* = \frac{M}{m_{st}\alpha_{st}H_{st}}$$

where:

m_{st}: the bending moment at the base of the superstructure.

T_{cap} and α_{st} denote the shear force induced at the cap and the acceleration of the superstructure mass.

H_{st}: superstructure height.

Influence of Nonlinearity of Concrete Piles

Results

The numerical simulations were carried out for the case of frictional soil (C=2 kPa, φ=30°,ψ=20°) under seismic loading recorded in Turkey (1999) with maximum amplitude (V_{max} = 0.4 m/s). The results obtained in the case of linear behavior of concrete piles were compared with the results obtained for elasto-plastic behavior of the piles and plastic bending moment M_p = 500 kN.m, which is the maximum moment the piles can support. The results show a significant decrease in the internal forces induced in the piles with the nonlinear behavior of the piles. This result is confirmed in Figure 3 and Table 4. The acceleration of the superstructure for elastic pile behavior is (23.5 %) higher than that obtained for elastoplastic behavior. The comparison of elastic and elastoplastic responses (Table 4) reveals a reverse trend for the acceleration at the cap. The profile of bending moment shows that plasticity has attained over a large part of the pile and is not located only in the pile head (plastic hinge). This result shows that the collapse of the structure is very probable with the elastoplastic behavior of the piles. On the other hand, we note that only in case of nonlinear behavior of the piles, we obtain a reduction of maximum normal forces by about (24.6%) and (34%) for maximum shear forces in external piles. Also, there is an attenuation in the spectral amplitude of the structure velocity as shown in Figure (4). This is due to the damping induced by the plasticity of the piles. It is important to note that the presence of plasticity in the piles influences the distribution of the maximum shear forces between the central and external piles.

Table 4. Influence of nonlinear behavior of concrete pile on dynamic forces in piles (frictional soil, earthquake of Turkey, V_g = 40 cm/s)

Model (Concrete)	α_{st} (m/s²)	α_{Cap} (m/s²)	Dynamic Forces						Normalized Forces	
			Central Piles			Corner Piles			Corner Piles	
			N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)	T_{max}	M_{max}
Elastic	9.567	6.592	38.2	511.7	897.9	1840.2	917.3	1140	0.211	0.062
Plastic M_p=500 kN.m	7.744	8.327	38.8	450.8	500	1386.2	604.1	500	0.154	0.033

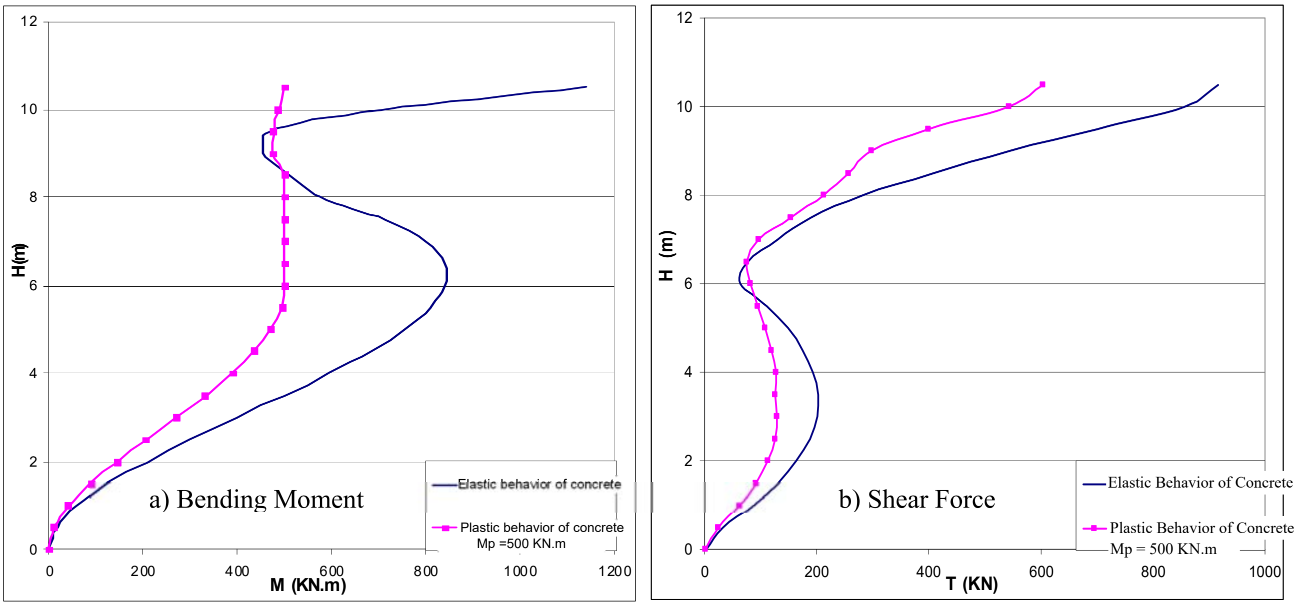


Figure (3): Influence of nonlinear behavior of concrete pile on dynamic forces in the corner piles (frictional soil, earthquake of Turkey, V_g = 40 cm/s)

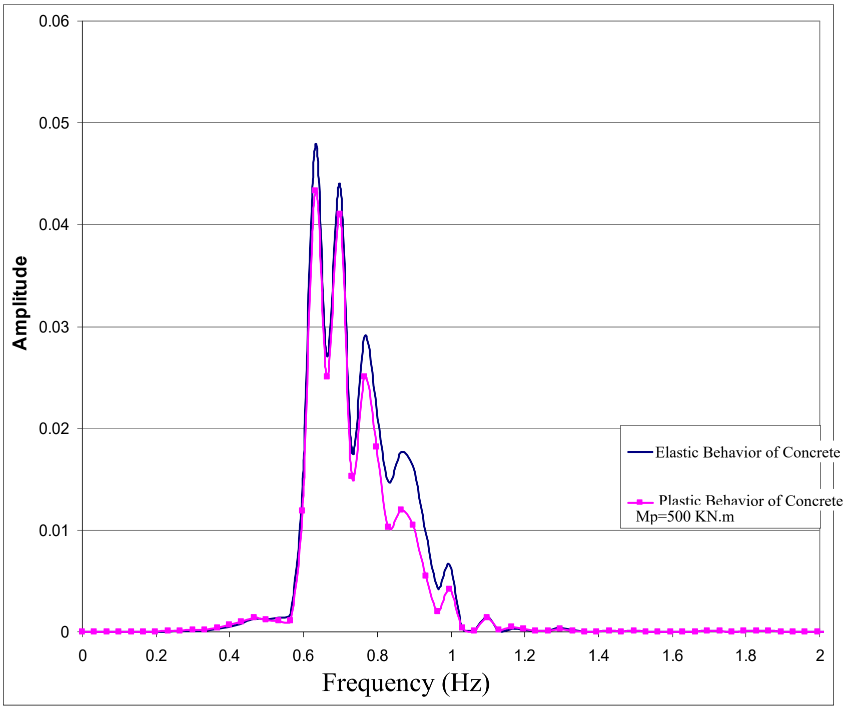


Figure (4): Influence of nonlinear behavior of concrete pile on the superstructure head spectral velocity (Fourier spectra diagram)
(frictional soil, earthquake of Turkey, V_g = 40 cm/s)

Piles' Interaction Reinforcement

The site observations of (Lizzi and Carnevale, 1981; Pearlman et al., 1993, Mason, 1993; Herbst, 1994), as well as recent research, have demonstrated that the micropiles' system constitutes a reliable tool as reinforcement technique for existing structures. The facility of installation, especially in difficult access locations, represents its main asset. The use of such system in seismic sites provides great benefits, because this system of foundations is characterized by good flexibility and ductility, which are very appreciated properties for structures exposed to seismic risks. In the field of numerical modeling, the main research on the seismic behavior of micropiles focused on their use as foundation of new structures (Sadek, 2003; Al Saleh, 2006). In this part, we examine the response of soil-pile-structure system reinforced by a group of micropiles. The model used is an identical system to that previously studied with a foundation of (6) piles that will be reinforced by a group of (4) micropiles (2*2). The micropiles' diameter is D_m = 0.25 m (Figure 5). The implementation of the reinforcement solution used takes place by enlarging the existing cap in which the micropiles will be built in order to rigidify the foundation system. The interface between the piles or micropiles and the soil is supposed elastic. The calculations were carried out with assuming the value of piles' plastic moment M_p=500 kN.m. The applied loading is the record of Turkey (1999), but with a maximum amplitude (V_{max}= 0.6 m/sec).

This amplitude was chosen in order to induce the development of plasticity over a large part of the piles, which justifies the reinforcement. The soil characteristics are identical to those used in the previous sections (frictional soil: C=2 kPa, φ=30°,ψ=20°). In order to limit the number of reinforcement elements (4 elements) and perform a qualitative analysis, the behavior of the micropiles will be assumed to be linear elastic, even if the induced forces exceed their bearing capacity. For a real study, the number of micropiles must be optimized according to applied seismic loading.

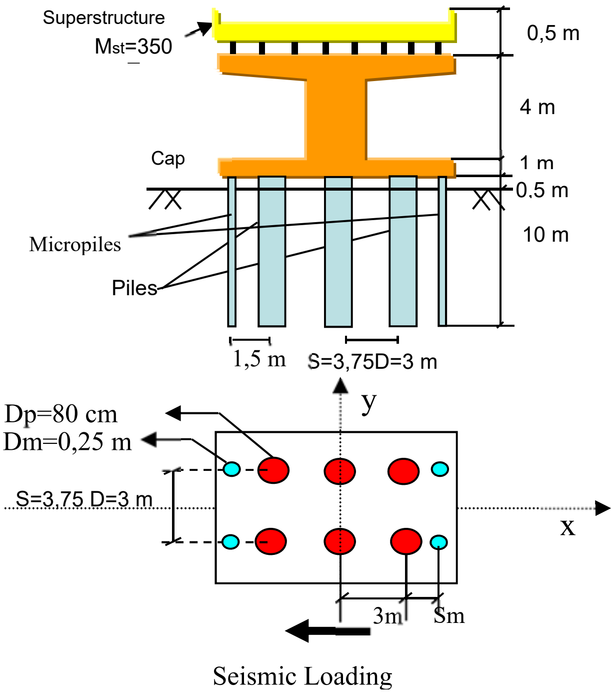


Figure (5): Micropile reinforcement scheme

Effect of Pile-Micropile Spacing

In order to analyze the influence of pile-micropile spacing on the seismic response of the system, numerical simulations were carried out for several values of pile-micropile spacing (S_m= 1.5, 2 and 3 m). Tables (5 and 6) and Figure (6) give the results of the comparison between system response before and after reinforcement for several pile-micropile spacings. Firstly, it is noted that reinforcement with micropiles can constitute an effective reinforcement solution. In fact, there is a strong reduction in the internal forces in the piles after reinforcement. Figure (6) compares the bending moment envelopes in the piles with and without reinforcement. After reinforcement, we note that the plasticized area of the pile is reduced to a point located at the head of the pile, which can be accepted by seismic codes and does not jeopardize the structure. Furthermore, it can be seen that the maximum bending moment decreases with the increase of pile-micropile spacing. A similar tendency is observed for the shear force envelope in the pile. The reinforcement incites a reduction of the normal force by about (45%) in the pile head. The influence of pile-micropile spacing is not very significant despite a small decrease of the internal forces with the spacing increase. In terms of the normal forces induced in the piles, the reinforcement was very beneficial in reducing the forces taken by the piles. In fact, a 75% attenuation of the maximum normal force in the piles after reinforcement is obtained. However, the influence of pile-micropile spacing on the normal force in the piles is not important, but it incites a significant attenuation of normal force in the micropiles. By examining the spectral response of the velocity at the top of the superstructure (Figure 7), we note a decrease in the maximum amplitude with the increase of pile-micropile spacing. This reflects an increase in the stiffness of the structure and explains the reduction of the dynamic forces in the piles. This result agrees with those obtained by Sadek (2003) concerning the increase in the rigidity of the system and the reduction of the lateral amplification with the spacing. Figure (8) shows the envelope of the bending moment and shear force induced in the micropiles under seismic loading. It can be seen that the spacing does not have a significant effect on the distribution of these forces. These results confirm the measurements performed in centrifuges by Fukui et al. (2001).

Table 5. Influence of nonlinear behavior of concrete pile on dynamic forces in piles

Model (Concrete) M_p = 500 (kN.m)	A_{cc} mass (m/s²)	A_{cc} Cap (m/s²)	Dynamic Forces					
			Central Piles			Corner Piles		
			N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
Before reinforcement	8.712	14.25	36.3	489.1	500	1553.2	691.5	500
After reinforcement S=1.5 m	8.432	8.4	8.6	289.1	500	376	359.6	500
After reinforcement S=2 m	8.358	8.759	0.5	281.9	500	422.6	339.7	500
After reinforcement S=3 m	7.608	8.131	0.4	247.2	500	331	291	500

Table 6. Influence of pile-micropile spacing on the dynamic forces in the reinforcing micropiles

Model	Dynamic Forces (Micropile)		
	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
S=1.5 m	984	602.7	1090
S=2 m	841.3	596.6	1080
S=3 m	594	491.4	926.8

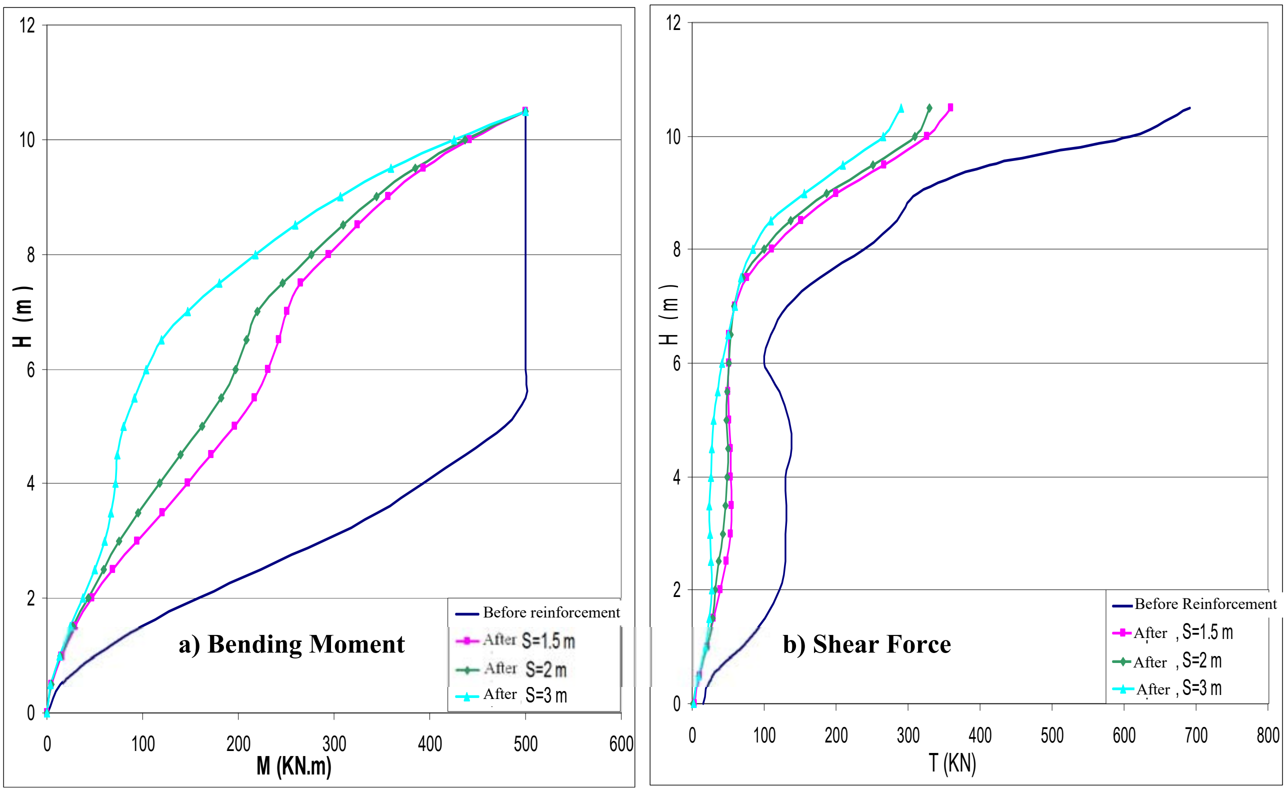


Figure (6): Influence of pile-micropile spacing on dynamic forces in the corner piles

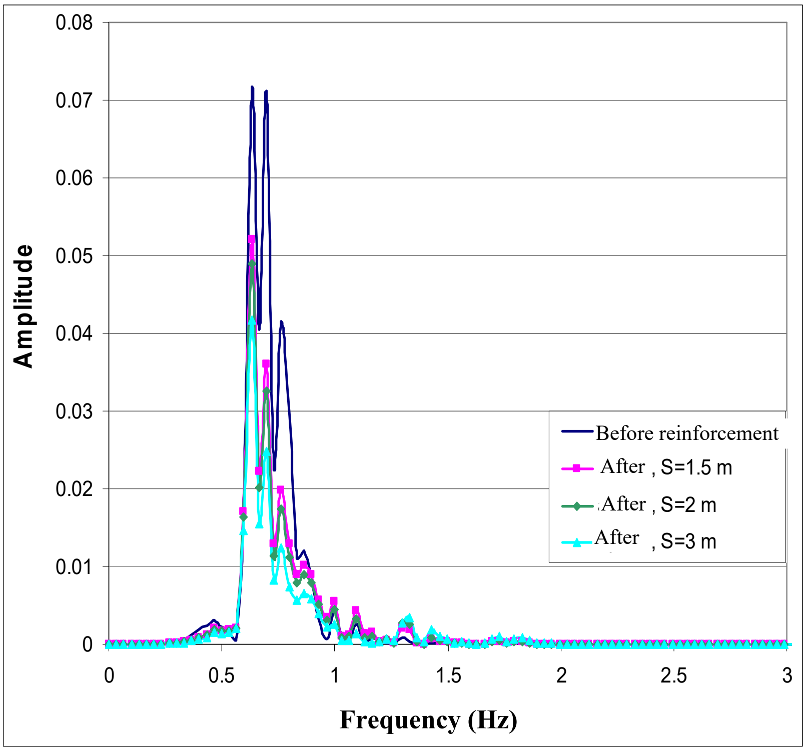


Figure (7): Influence of pile-micropile spacing on the superstructure head spectral velocity

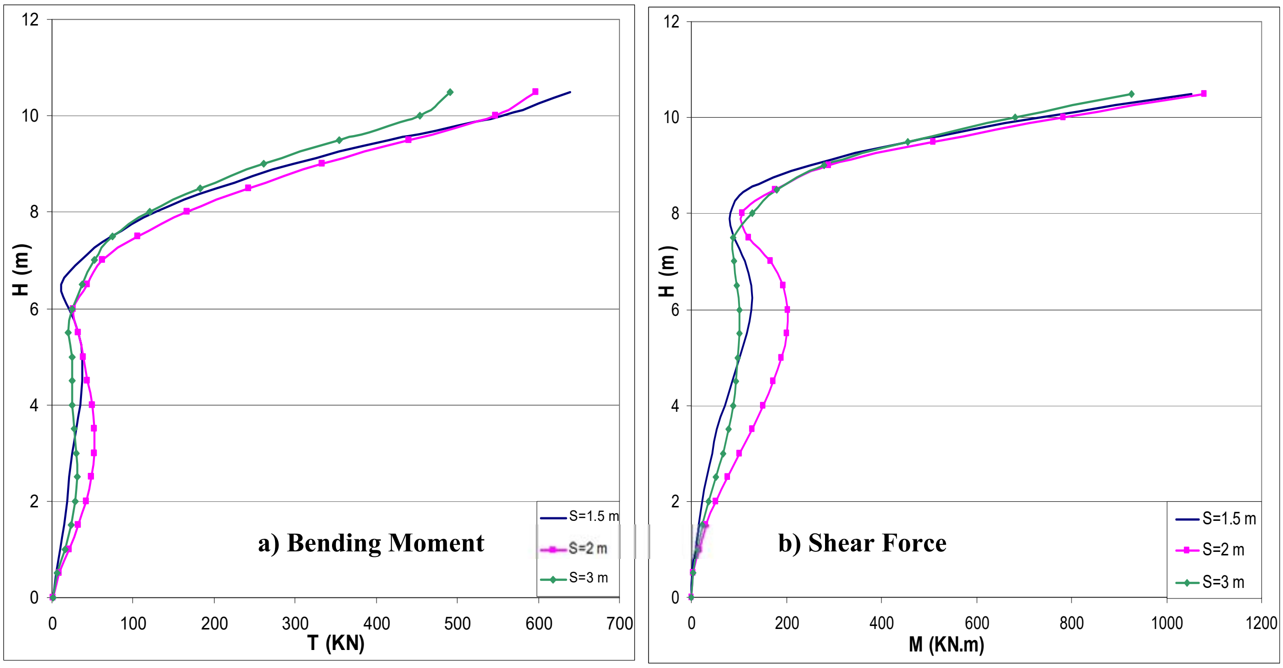


Figure (8): Influence of pile-micropile spacing on the dynamic forces in the reinforcing micropiles

Effect of Micropile Connection

In this section, we propose to analyze the effect of the micropile-cap connection on the seismic response of the system. Two types of connection are studied: fixed and articulated. The analysis is carried out for pile-micropile spacing (S=2 m). Figures (9 and 10) and Tables (7 and 8) present the results obtained for the two studied cases. By checking the induced forces in the piles, we note that reinforcement by fixed micropiles reveals better efficiency in comparison with articulated micropiles. For articulated micropiles, the plastic moment has attained the upper quarter of the pile. Furthermore, the maximum shear force of the piles obtained in the case of articulated micropiles is higher by (25-35 %) than the one obtained in the case of reinforcement by fixed micropiles. This result is accompanied by the increase of cap acceleration, which reflects lower rigidity for the system in the case of reinforcement with articulated micropiles. The normal effort shows comparable maximum values in both cases (fixed, articulated). Concerning the internal forces developed in the micropiles, the presence of articulation permits to relieve the induced internal forces in the pile head. In that case, the maximum moment obtained at a depth of (2 m) of the micropile is considerably less than that developed at the top of the fixed micropiles (M=1080 kN.m). This result is consistent with the results found by Sadek (2003). The profile of the shear force also shows a decrease in the case of articulated micropiles , which is not in favor of the internal forces induced in the existing piles.

Table 7. Influence of micropile/shear connection on the dynamic forces in the piles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

Model (Concrete) M_p = 500kN.m	A_{cc} mass (m/s²)	A_{cc} Cap (m/s²)	Dynamic Forces					
			Central Piles			Corner Piles		
			N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
Fixed Micropiles	8.358	8.759	0.5	281.9	500	422.6	339.7	500
Articulated Micropiles	8.179	14.28	18.7	381.2	500	406.1	499.4	500

Table 8. Influence of micropile/shear connection on the dynamic forces in the micropiles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

Model	Dynamic Forces		
	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
Fixed	841.3	596.6	1080
Articulated	655.8	359	529.7

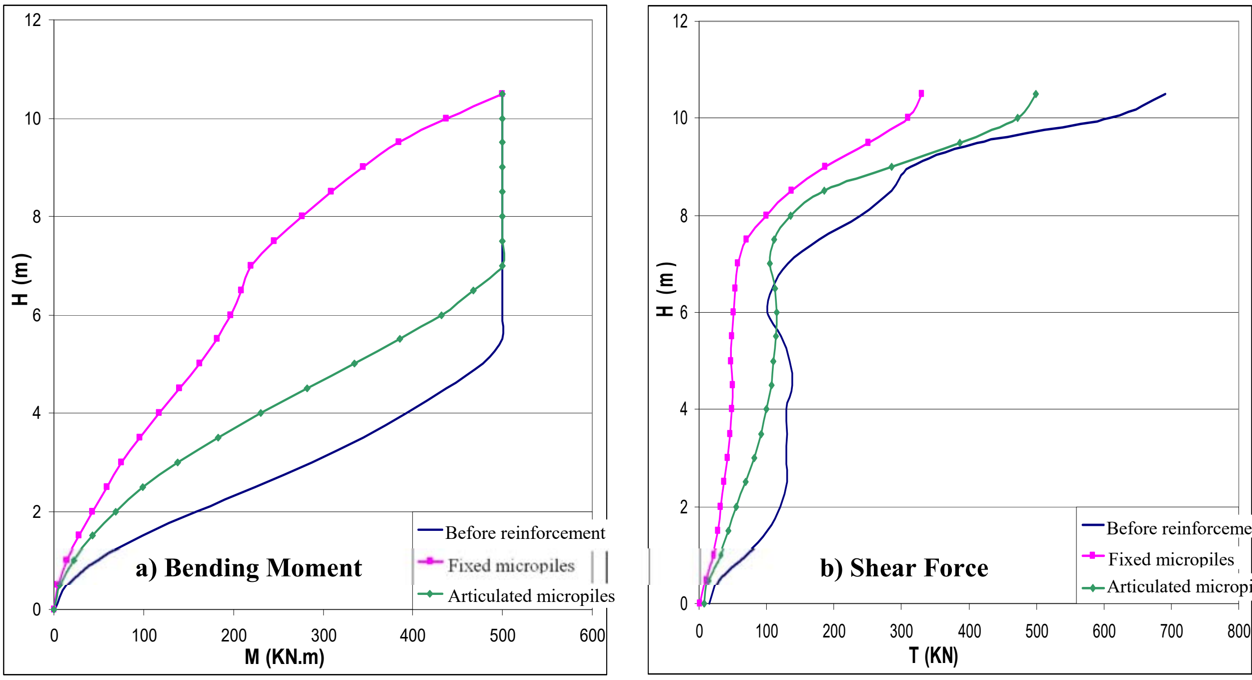


Figure (9): Influence of micropile/shear connection on the dynamic forces in the corner piles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

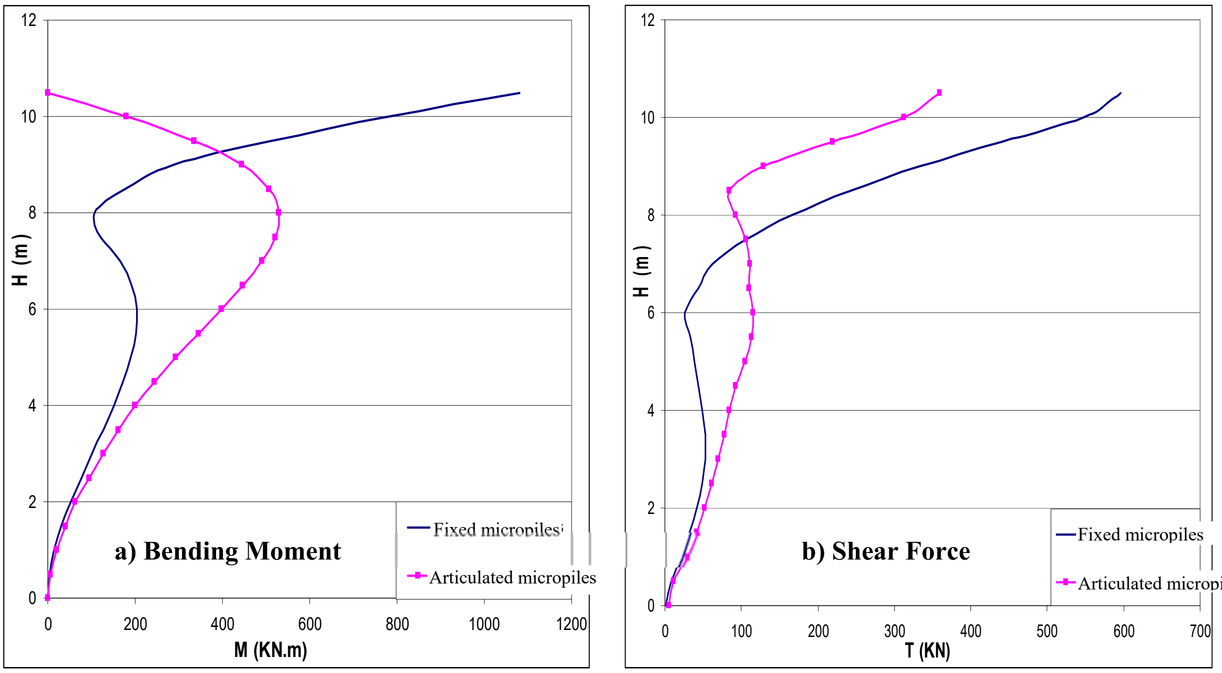


Figure (10): Influence of micropile/shear connection on the dynamic forces in the micropiles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

Effect of inclination of the micropiles

In this section, we are interested in the analysis of the effect of the inclination of the micropiles, which can be beneficial as already reported by Sadek (2003) and Al Saleh (2006) for micropiles used as new foundations. We study the influence of inclination on the response of the existing structure (superstructure + piles) as well as on the response of the micropiles themselves. The soil-pile and soil-micropile connections are assumed to be perfectly rigid. Figures (11 and 12) and Tables (9 and 10) present the results of numerical simulations carried out for two inclinations of the micropiles (α = 0° and α= 15°) in the case of frictional soil (C=2 kPa, φ=30°, ψ=20°). In the case of inclined micropiles, we note a considerable decrease in the shear force accompanied by an attenuation in the lateral acceleration at the superstructure and the cap. This decrease in the shear force is in the order of (30%) compared with the vertical reinforcement. Concerning the bending moment in the piles, the plastic moment has attained at the pile heads in both cases, In the case of inclined micropiles, a significant attenuation is observed in the upper half of the piles. The inclination is also very beneficial for the normal force induced in the piles, where a considerable reduction of the normal force is obtained. This beneficial effect of the inclination confirms the results of the tests carried out in centrifuges by Fukui et al. (2001). By examining the forces induced in the reinforcing micropiles, it can be seen that the inclination of the micropiles results in a significant reduction in the maximum shear force and bending moment. This reduction attains (53%) for the shear force and (42%) for the bending moment, which significantly improves the strength of the reinforcement elements without jeopardizing the existing piles. It should be noted that the inclination of the micropiles leads to a moderate increase (15%) of the normal force in the micropiles.

Table 9. Influence of inclination of the micropiles on the dynamic forces in the piles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

α (°)	A_{cc} mass (m/s²)	A_{cc} Cap (m/s²)	Dynamic Forces					
			Central Piles			Corner Piles		
			N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
0	8.358	8.759	0.5	281.9	500	422.6	329.7	500
15	6.473	6.897	0.3	206.5	500	126	231.9	500

Table 10. Influence of inclination of the micropiles on the dynamic forces in the micropiles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

α (°)	Dynamic Forces		
	N_{max} (kN)	T_{max} (kN)	M_{max} (kN.m)
0	841.3	596.6	1080
15	978.5	276	624

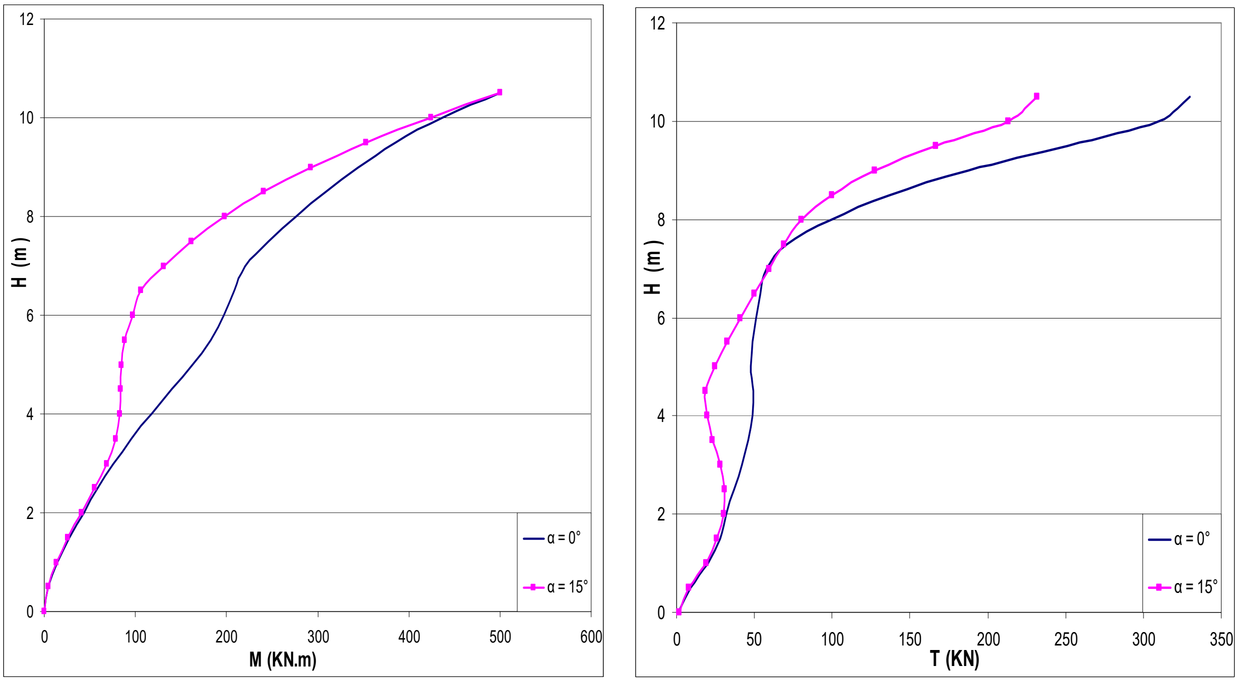


Figure (11): Influence of inclination of the micropiles on the dynamic forces in the corner piles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

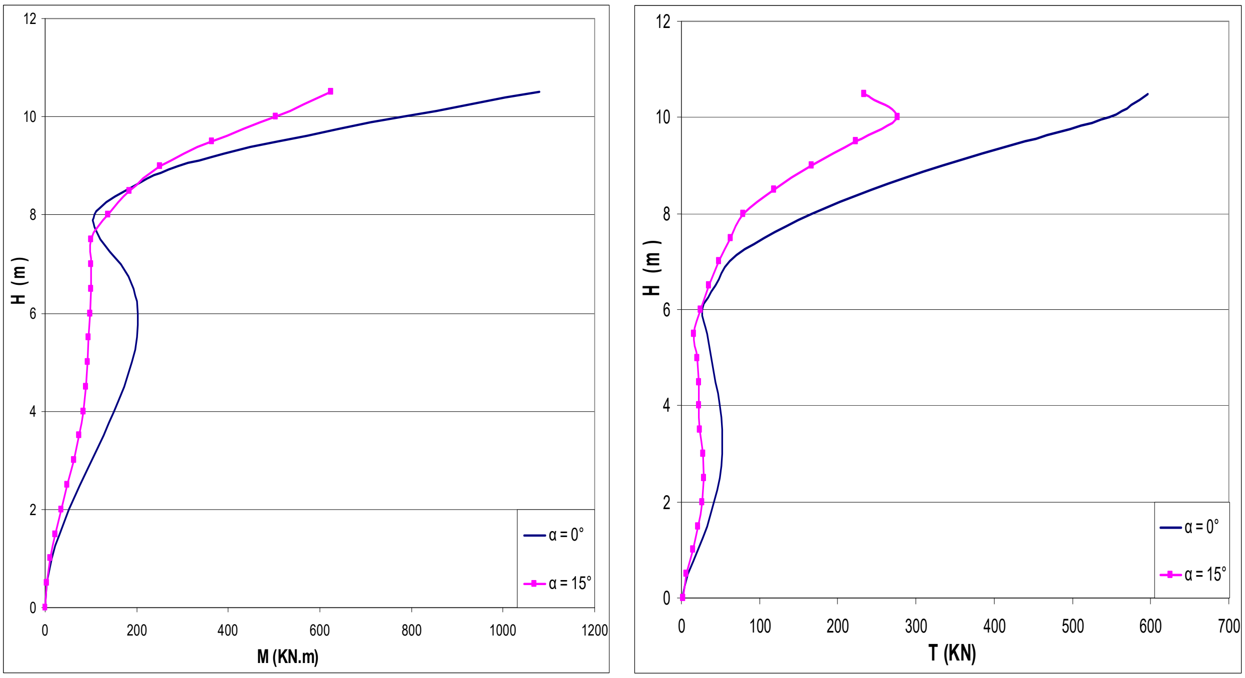


Figure (12): Influence of inclination of the micropiles on the dynamic forces in the micropiles (frictional soil (φ=30°, C=2 kPa, ψ=20°), earthquake of Turkey, V_g = 60 cm/s)

CONCLUSIONS

This study was devoted to global numerical modeling of soil-pile-bridge interaction problem under seismic loading. Attention was particularly given to the influence of soil nonlinearity and development of plastic hinges in piles. The research within the domain of this study was conducted using a three-dimensional finite differences' modeling program (FLAC 3D). The consideration of non-linear behavior of concrete is important, especially if the bearing capacity of the concrete is likely to be exceeded. It permits better prediction of system failure under any load. The development of plastic hinges leads to an attenuation of the overall response of the system. It is found that the plasticizing of the piles changes the report of distribution of shear and normal forces between the central and external piles. This type of behavior permits to predict the failure of the system in the case of plasticity extension in the concrete piles, which is not the case with a linear behavior. On the other hand, it permits an analysis of the behavior of an existing structure requiring reinforcement. The results confirm the efficiency of the reinforcement system with micropiles for existing piles. The implantation of reinforcement elements plays a decisive role in the response of the system. Parametric study of the reinforcement system (pile-micropile spacing, micropile connection and micropile inclination) was carried out. The results reveal a slight effect of pile-micropile spacing on the response of the system. The fixing of micropiles in the cap allows a better attenuation of the forces in the piles and the structure. Similarly, the use of inclined micropiles as reinforcing elements is very beneficial to existing piles and micropiles themselves. These conclusions confirm the results of recent centrifuge tests on groups of piles reinforced by micropiles

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